High-Dilution Stoichiometric Gasoline Direct-Injection (SGDI) Combustion Control Development

Project ID # ACE090

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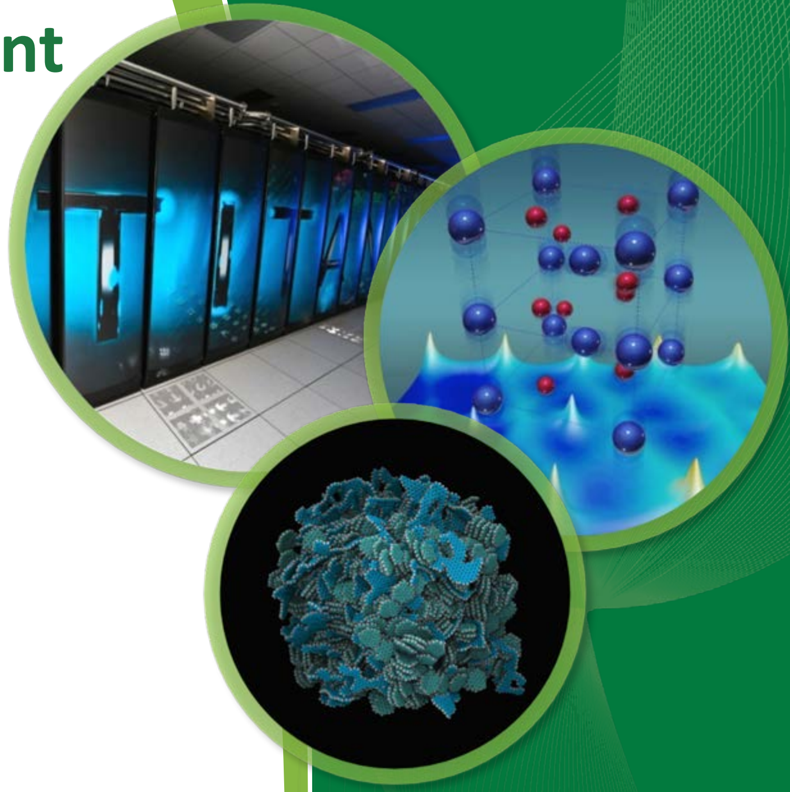
Advanced Combustion Engines R&D

Vehicle Technologies Office

U.S. Department of Energy

2016 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

June 7, 2016



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High-dilution SGDI project overview

Timeline

- Evolution of a project that began in 2011
- Current trajectory began in 2013

Barriers (MYPP §2.3.1 A, D)

- Lack of fundamental knowledge of advanced engine combustion regimes
- Lack of effective engine controls

Budget

- FY 2014: $300k
- FY 2015: $200k
- FY 2016: $200k

Partners/Interactions

- Collaborations
  - Bosch
  - National Instruments
  - Argonne National Laboratory
  - Internal collaboration with diagnostic and computing efforts (ACE 017 & ACE 077)
- Presentations/Interactions at AEC Program Review (MOU) Meetings

Objective: Develop advanced control strategies to extend SI dilution limits

Project Objective

Development and demonstration of predictive control methodologies that exploit the deterministic nature of cyclic dispersion and abnormal combustion to stabilize inherently unstable combustion processes for higher efficiency.

- FY 15-16 Objectives
  - Characterize cyclic variability for external EGR operation
  - Evaluate implications of long-timescale EGR feedback for symbol sequence control methods
  - Integrate EGR flow model with symbol sequence prediction
  - Begin investigation of model-based approaches to prediction and control of cyclic variations

Goal of Advanced Combustion Engines R&D

"… improve the fuel economy of light-duty gasoline vehicles by 25 percent and of light-duty diesel vehicles by 40 percent, compared to the baseline 2009 gasoline vehicle." (MYPP 2011-2015 §2.3.1)

All tracked milestones have been completed or are on-track

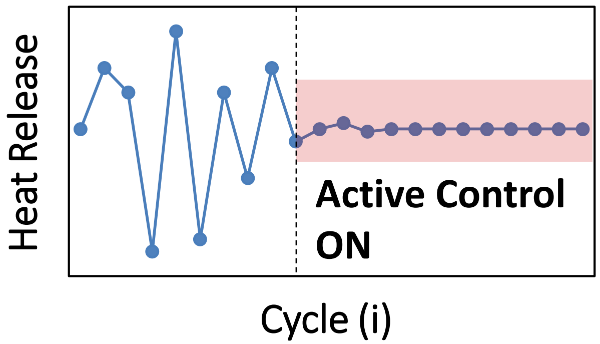
Month/Year	Milestone	Status
06/2015	Demonstrate impact of combined control strategies on EGR dilution limit extension	Completed
09/2015	Demonstrate applicability of next-cycle control strategy to homogeneous lean combustion	Completed
06/2016	Demonstrate control-oriented model for cyclic variability with external EGR feedback	On Track
09/2016	{SMART} – Evaluate effectiveness of combined model & symbol-sequence approach for prediction of cycle-to-cycle variations	On Track

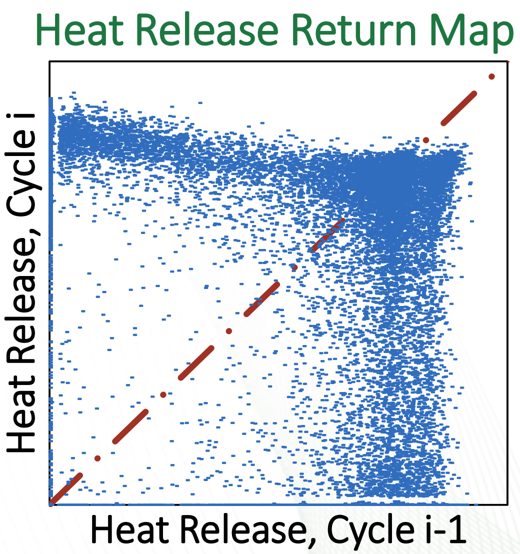
Advanced controls use deterministic behavior to reduce cyclic variability

- Combustion instabilities at the dilution limit have deterministic structure combined with stochastic noise

Determinism implies controllability

- Leverage ORNL's extensive background in identifying dynamical structure in noisy and chaotic time series
- Utilize tools from nonlinear dynamics and information theory to predict and control deterministic variations
- Enable operation at the "edge of stability"





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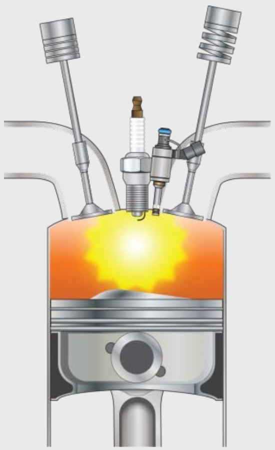
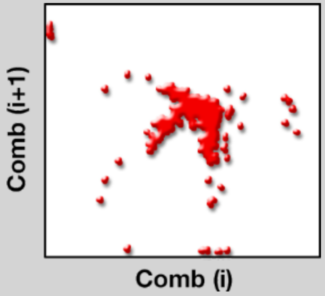
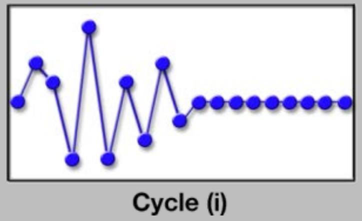
Characterize, Predict, and Control Chaos

APPROACH (2/3)

Characterize	Predict	Control
Advanced Diagnostics	**Nonlinear Dynamics**	**Advanced Controls**
• Characterize cyclic variability • Enhance understanding of feedback mechanisms	• Data interpretation • Simulation • Pattern recognition • Prediction	• Take advantage of determinism to stabilize combustion • Leverage advanced modeling efforts







Leverage ORNL's unique computational and diagnostic capabilities

Approach (3/3)

Advanced diagnostics enhance understanding of physical processes

- Real-time combustion diagnostics provide feedback for control
- Fast measurements of composition in EGR stream
- Leveraging capabilities developed in ACE 077 Cummins CRADA

ORNL's leadership computing capabilities enable accurate modeling of multi-cycle events

- Coordinating with ACE 017 HPC project
- Computationally inexpensive meta-models developed from results will be utilized in future prediction & control efforts

Application of advanced controls on modern automotive engine platform

- Utilize knowledge gained from diagnostics
- Apply models developed in computing effort
- Demonstrate real-time control on engine

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Accomplishments—Overview

- Built further understanding of cycle-to-cycle dynamics
  - Evaluation of temporal resolution of external EGR feedback for varying EGR rates
  - Evaluation of cycle-to-cycle dynamics with combined internal/external EGR approach
- Progress in control-oriented predictive model development
  - Exploring low-order model options and evaluating predictive capabilities
  - Supporting high-performance computing modeling efforts to develop meta-models that will be more effective in the long run

PHILOSOPHICAL TRANSACTIONS A

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Characterizing dilute combustion instabilities in a multi-cylinder spark-ignited

SAE INTERNATIONAL

Impact of Delayed Spark Restrike on the Dynamics of Cyclic Variability in Dilute SI Combustion

2016-01-0691
Published 04/05/2016

Gurneesh S. Jatana, Brian C. Kaul, and Robert Wagner
Oak Ridge National Laboratory

CITATION: Jatana, G., Kaul, B., and Wagner, R., "Impact of Delayed Spark Restrike on the Dynamics of Cyclic Variability in Dilute SI Combustion," SAE Technical Paper 2016-01-0691, 2016, doi:10.4271/2016-01-0691.

Abstract

Introduction

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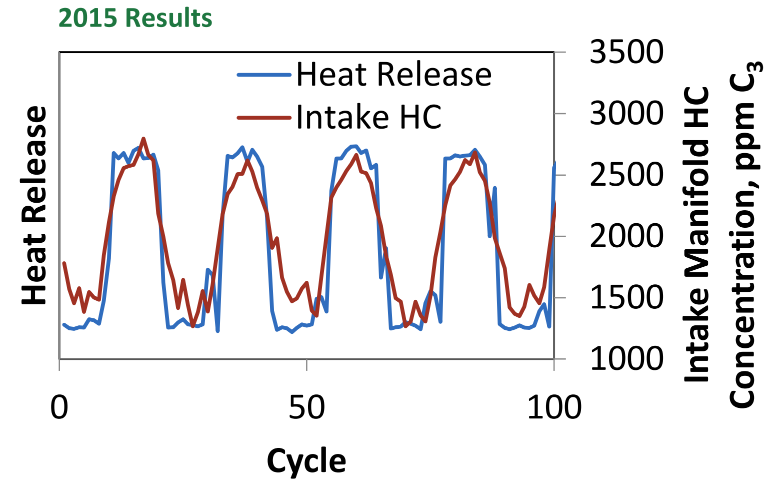
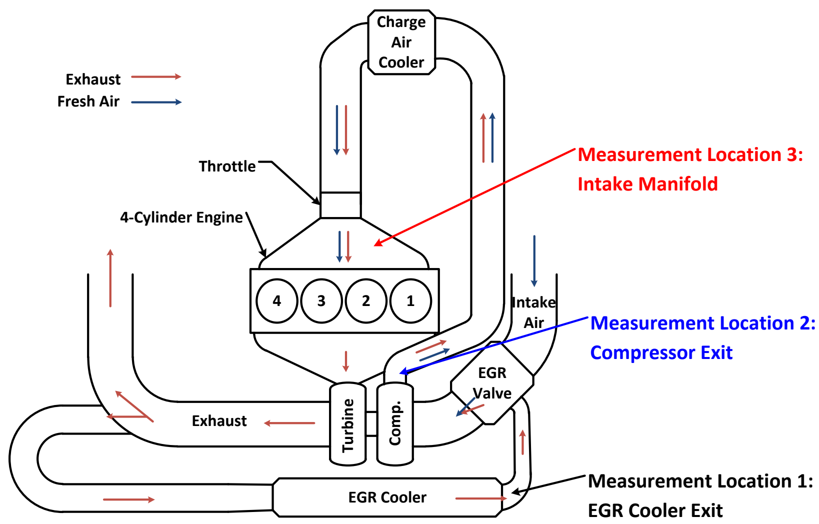
Evaluation of temporal resolution of external EGR feedback for varying EGR rates

- Prior year results showed clear coupling between EGR composition and combustion quality for extremely high EGR rates
  - Implied need to restructure symbol sequence analysis to consider long timescales and firing order
  - Raised question of whether the same effect would be observed at lower EGR levels



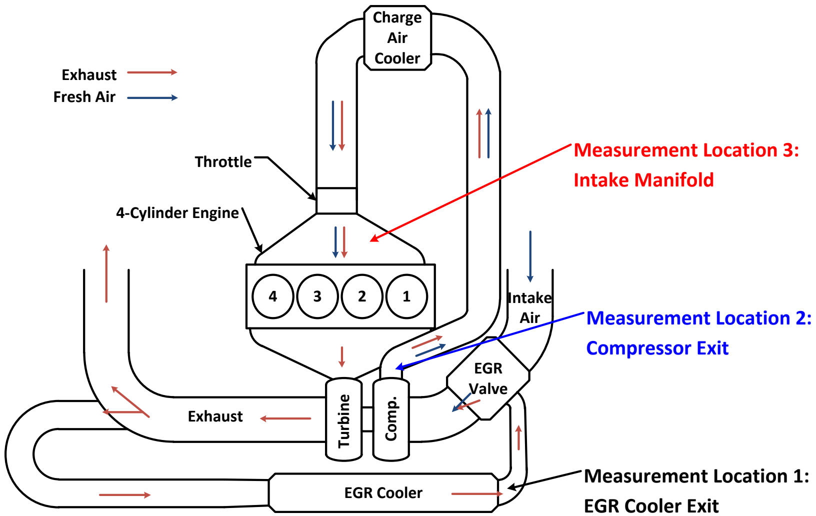


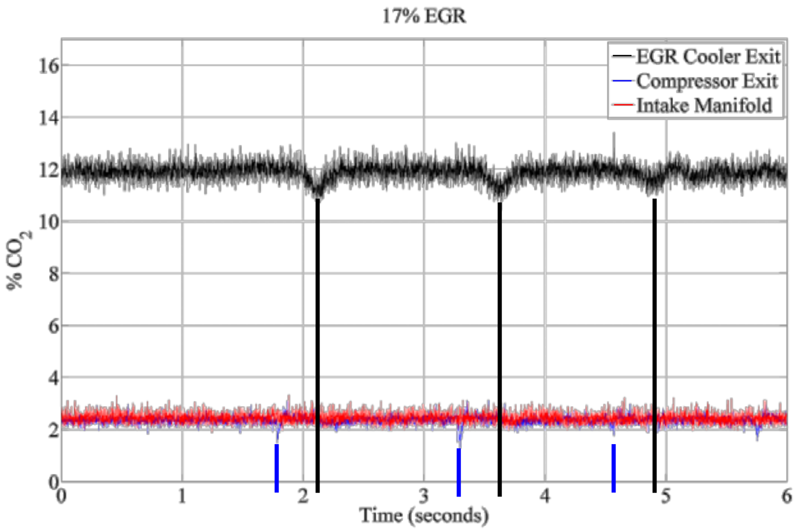
- Fast EGR probe from Cummins Combustion CRADA (ACE 077) used to determine temporal resolution of EGR feedback
  - Probe allows simultaneous 5 kHz (2.4°CA at 2000 rpm) sampling at multiple locations
  - Experiments evaluated time response of system to both fast and slow changes in CO_2 concentration

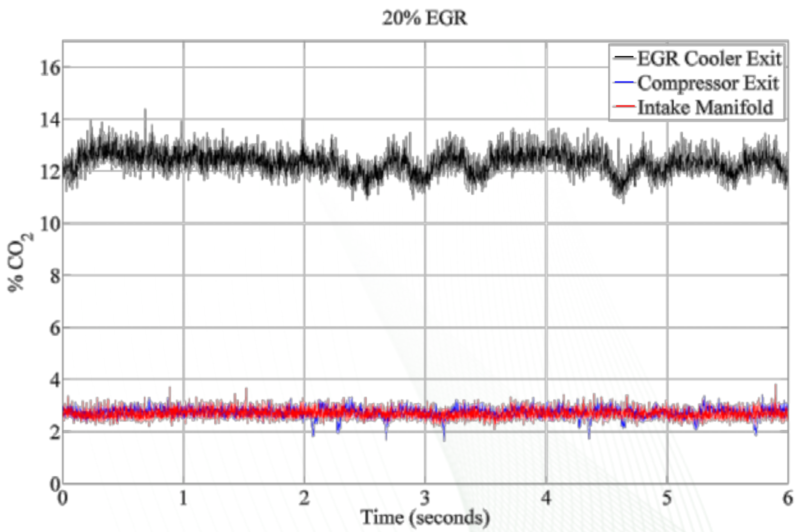
External EGR loop acts as low-pass filter on cycle-to-cycle feedback

ACCOMPLISHMENTS (3/7)

- For moderate EGR levels, individual-cycle response is not preserved all the way through the flow path
  - Rapid variations present at the EGR cooler exit and compressor exit do not appear at the intake manifold
- Effects of weak combustion cycles are seen at compressor exit 0.3s *before* EGR cooler exit
  - Turbomachinery reacts to enthalpy change faster than compositional effects are transmitted through the flow path, resulting in momentary drop in EGR flow rate







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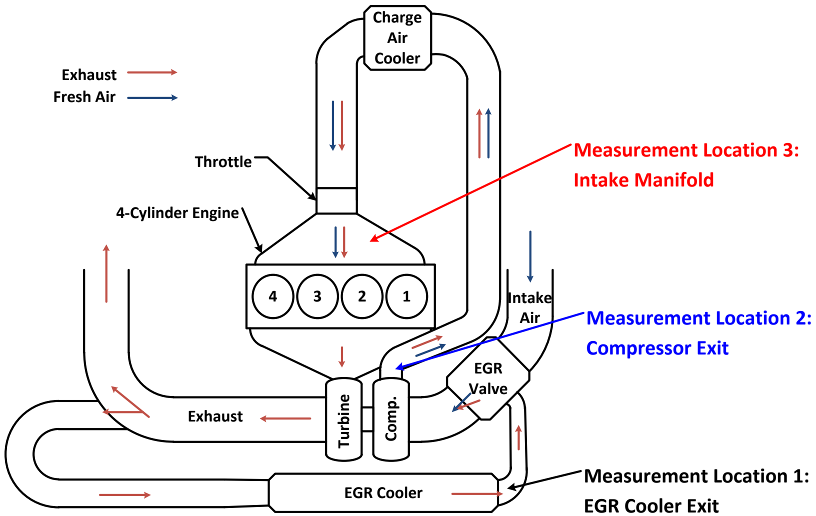
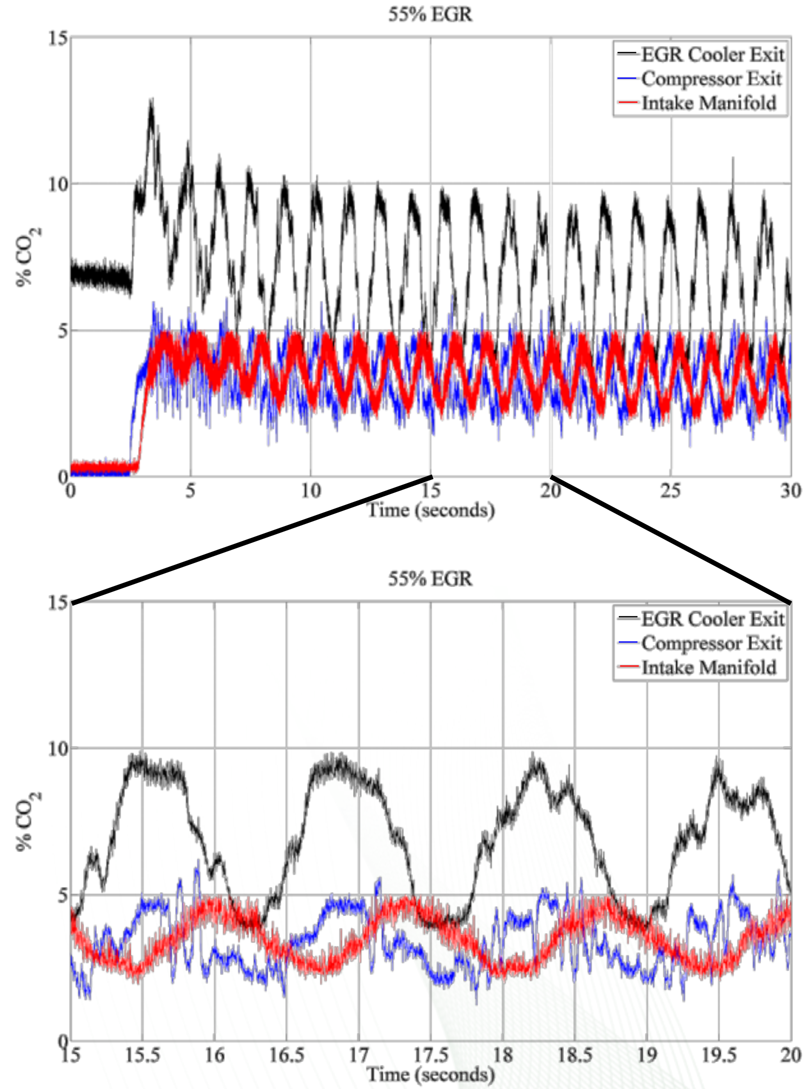
External EGR loop acts as low-pass filter on cycle-to-cycle feedback

ACCOMPLISHMENTS (4/7)

- At very high EGR levels, composition variations are preserved, consistent with previous experiments
  - Composition changes are communicated through the EGR loop
  - Rapid variations present at the EGR cooler exit and compressor exit do not appear at the intake manifold
- Intake system components are acting as low-pass filters on composition feedback to future cycles

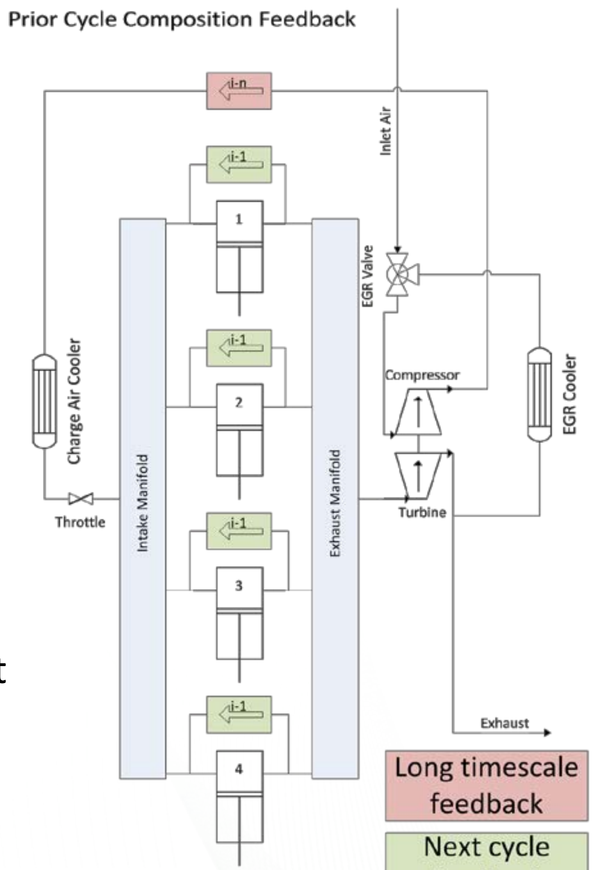




Residual gas/“internal EGR” provides next-cycle feedback

Accomplishments (5/7)

- Combined internal/external EGR operation can still achieve many benefits of external cooled EGR while increasing deterministic feedback potential
  - In this experiment, approximately half the dilution is from each
- COV reduced by 2% absolute (10% relative) in proof-of-concept experiment
  - Symbol sequence approach successfully identifies many of the cycles we want to correct
  - Simple on/off proportional control gain approach for initial test
  - Model-based approach needed for better control response
  - Further development will move towards stabilizing operation at more moderate dilution/COV levels



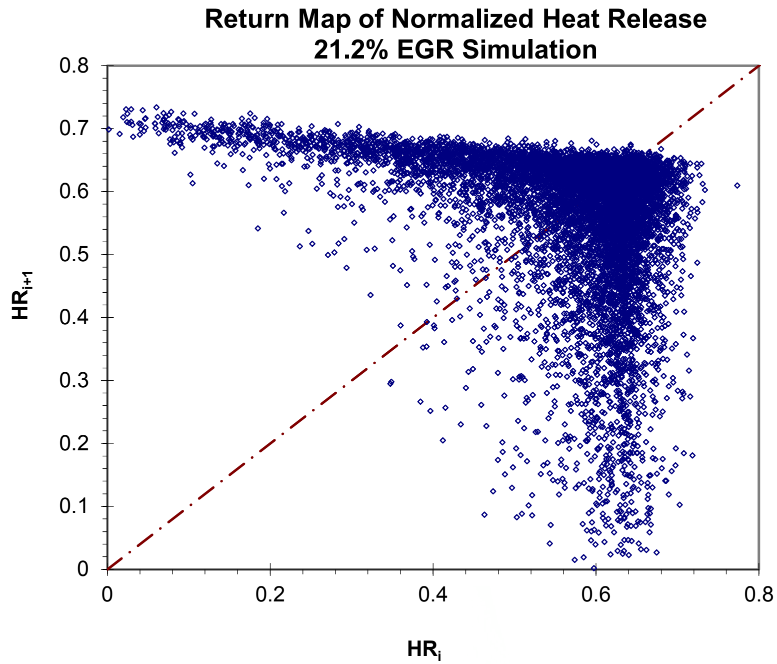
EGR (%)	RF (%)	Next Cycle	φ	COV Cyl 1	COV Cyl 2	COV Cyl 3	COV Cyl 4
13	14	Off	1.003	20.6	18.0	23.2	16.6
13	14	On	1.005	18.3	16.2	19	14.4

Low-order model adapted for real-time on-engine implementation

Accomplishments (6/7)

- Low-order model previously developed by Daw, et al.[1] for lean burn shows similar dynamics as engine data
  - Combustion efficiency (CE) assumed to be a nonlinear function of equivalence ratio (φ)
  - Tunable parameters φ_U and φ_L define response

$$CE = \frac{1}{1 + 100^{-\frac{\varphi - 0.5\cdot(\varphi_U + \varphi_L)}{\varphi_U - \varphi_L}}}$$

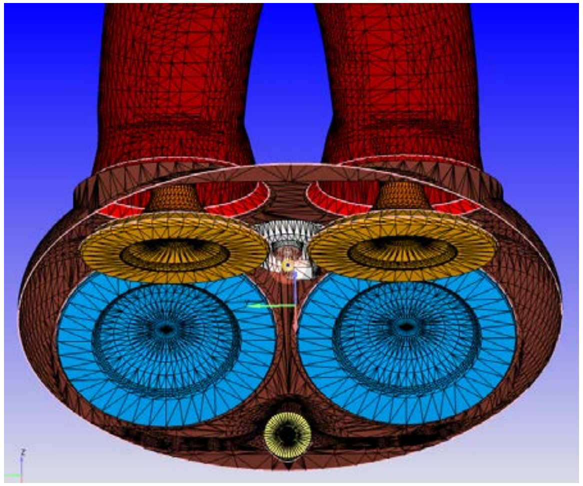


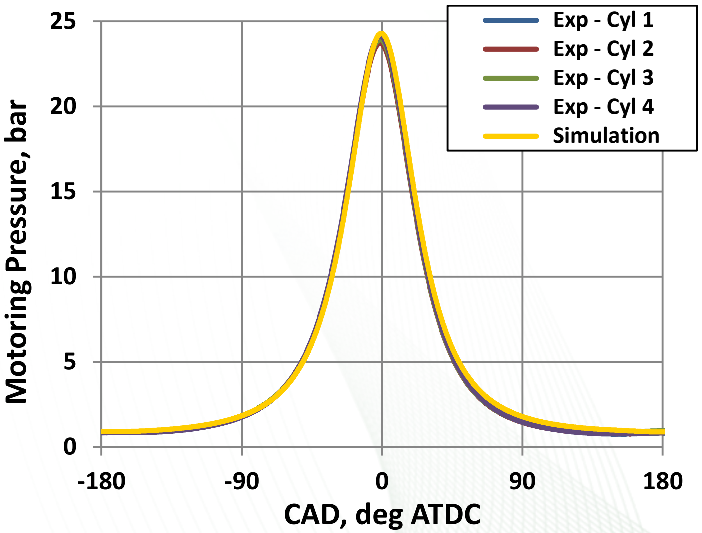
- Modified to account for EGR dilution through use of φ' effective equivalence ratio (considering EGR dilution as effectively equivalent to excess air)
- Adapted to work with engine data for air, fuel, and EGR charge mixture composition rather than simulated estimates from model input parameters + random noise
  - Currently evaluating with real data in post-processing in preparation to implement on-engine
  - Integration of EGR flow loop model to provide accurate information regarding EGR concentration in intake manifold is underway
- Options for more physically detailed models being evaluated, e.g. flame speed dependence on φ, etc.

1. Daw CS, et al., "A simple model for cyclic variations in a spark-ignition engine," SAE Technical Paper 962086.

Collaboration with HPC modeling effort to develop meta-models will enhance future control strategies

- Engine geometry has been measured and scanned to provide mesh information for HPC effort (ACE 017)
- Data have been collected to calibrate initial modeling efforts
  - Additional instrumentation (high-speed intake/exhaust port pressure) has been added to provide more detailed model validation data
  - Single-cycle simulations are progressing
- Meta-model results from HPC effort are expected to significantly enhance model-based control approach in future years
  - Computationally simple models for control
  - Based on highly detailed, physics-based simulations





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Reviewer comments from FY 2015

Reviewer comments paraphrased from 2015 AMR report

Positive comments

"The reviewer pointed out that this project very effectively addresses need for combustion stability control to enable high efficiency at part-load, highly-diluted GDI engine operation regime."

"The reviewer stated that it is actually surprising what has been done with the budget so far, but the progress is so good, have little doubt the team can continue to make progress …"

Responses to reviewer comments/suggestions

Reviewers indicated that the project should be more focused on demonstrating the benefit of a specific control algorithm.

Demonstration of an effective control algorithm remains the ultimate goal of this project. Additional work is required to further improve predictions and to develop control-oriented models that will enable effective control algorithms; the approach and plans for completing this work have been considered from this perspective, in order to focus on this goal rather than "trails of minor importance."

Reviewers expressed a desire to see more collaborations, especially from an OEM's controls experts.

This project has received general directional input from industry via presentations at the ACEC Tech Team and such forums, but we would welcome more direct OEM involvement. We have visited and presented results to one OEM, and we continue to seek the appropriate contacts at additional OEMs to develop effective collaborations.

"The reviewer noted that it would be good to quantify the potential opportunity to improve engine efficiency with this work. The reviewer suspected that it is fairly small."

The direct efficiency improvement possible due simply to reducing COV at a given dilution level can be quantified [1], and while it would be small for relatively low-COV operation, the potential gains from enabling the use of higher dilution levels and from resulting improvements in thermodynamic properties and combustion phasing at high loads, etc. are significant (i.e., > 10%) [2].

1. Kaul BC, Vance JB, Drallmeier JA, Sarangapani J. "A method for predicting performance improvements with effective cycle-to-cycle control of highly dilute spark-ignition engine operation," Proceedings of the Institution of Mechanical Engineers Part D - Journal of Automobile Engineering. 2009; 223(3): p. 423-438, doi:10.1243/09544070JAUTO943.

2. Alger, T., Mangold, B., Roberts, C. and Gingrich, J., "The Interaction of Fuel Anti-Knock Index and Cooled EGR on Engine Performance and Efficiency," SAE Int. J. Engines 5(3):2012, doi:10.4271/2012-01-1149.

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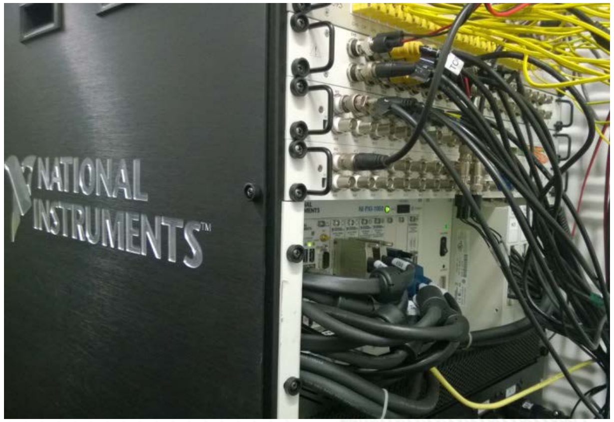
Collaborations

- National Instruments Powertrain Controls (Drivven)
  - Support of next-cycle and same-cycle controls development
- Argonne National Laboratory
  - Collaboration on analysis of effects of control perturbations in dilute SI combustion
- Robert Bosch LLC
  - High-compression GDI engine customized in previous DOE program
  - Provided engine and ECU with calibration-level access
- ORNL–Cummins Combustion CRADA (ACE 077)
  - High-resolution EGR measurements
- ORNL HPC Simulation Effort (ACE 017)
  - Providing experimental data for model development
  - Meta-model results will enhance future control efforts



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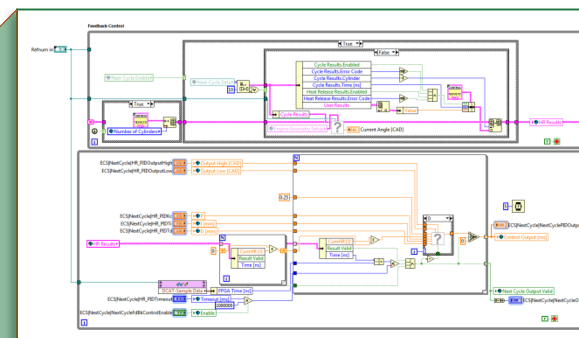
Remaining Challenges and Barriers

- Need to improve prediction for external EGR operation
  - Symbol sequence approach gives prediction of many problematic cycles
  - Low-order models present similar dynamics to dilute engine operation, but need enhancement to become predictive
  - HPC meta-modeling approach is promising (based on more detailed physics)
- Control strategies need further development
  - Symbol sequence approach yields predictions, but not the magnitude of control response required: simple proportional control is not appropriate for nonlinear system
  - Model-based approach will provide information to inform more advanced control strategies



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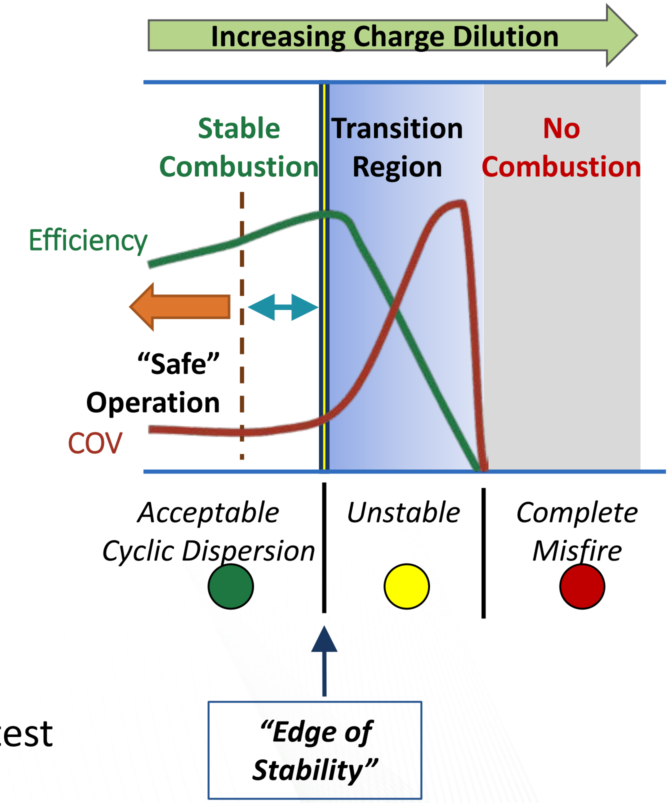
Future Work – proposed in current VTO Lab FOA

- Remainder of FY 2016
  - Development of low-order models for improved prediction
    - Extension of prior ORNL efforts for lean combustion to high-EGR operation
    - Inclusion of EGR flow path model
  - Integration with symbol sequence prediction technique
- FY 2017
  - Continue development of low-order models for real-time online prediction of cyclic variability
    - Begin development of control algorithms based on these models
  - Work with HPC modeling project to develop high fidelity control-oriented "meta-models" for improved prediction and control
- FY 2018
  - Implement low-order model-based control algorithms and test effectiveness for next-cycle control
  - Continue support of HPC efforts, with goal of implementing meta-models in FY 2019
  - Plans will evolve based on results from prior years



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Summary

Relevance

- Dilute combustion enables significant fuel efficiency gains in modern SI engines, but is limited by cyclic variability

Approach

- Utilize advanced diagnostic capabilities at ORNL to develop detailed knowledge of dynamics
- Apply results from high-performance computing effort to develop control-oriented models
- Take advantage of deterministic effects to stabilize combustion and extend practical dilute limit

Accomplishments

- Built further understanding of cycle-to-cycle and EGR feedback dynamics: needed to develop effective control strategies
- Progress in control-oriented predictive model development
  - Exploring low-order model options and evaluating predictive capabilities
  - Collaborating with HPC modeling effort to develop models which will aid control efforts

Collaborations

- Collaborating with other ORNL projects and with industry on high-EGR control system development

Future Work

- Developing and implementing next-cycle control strategies to enable operation on the "edge of stability"

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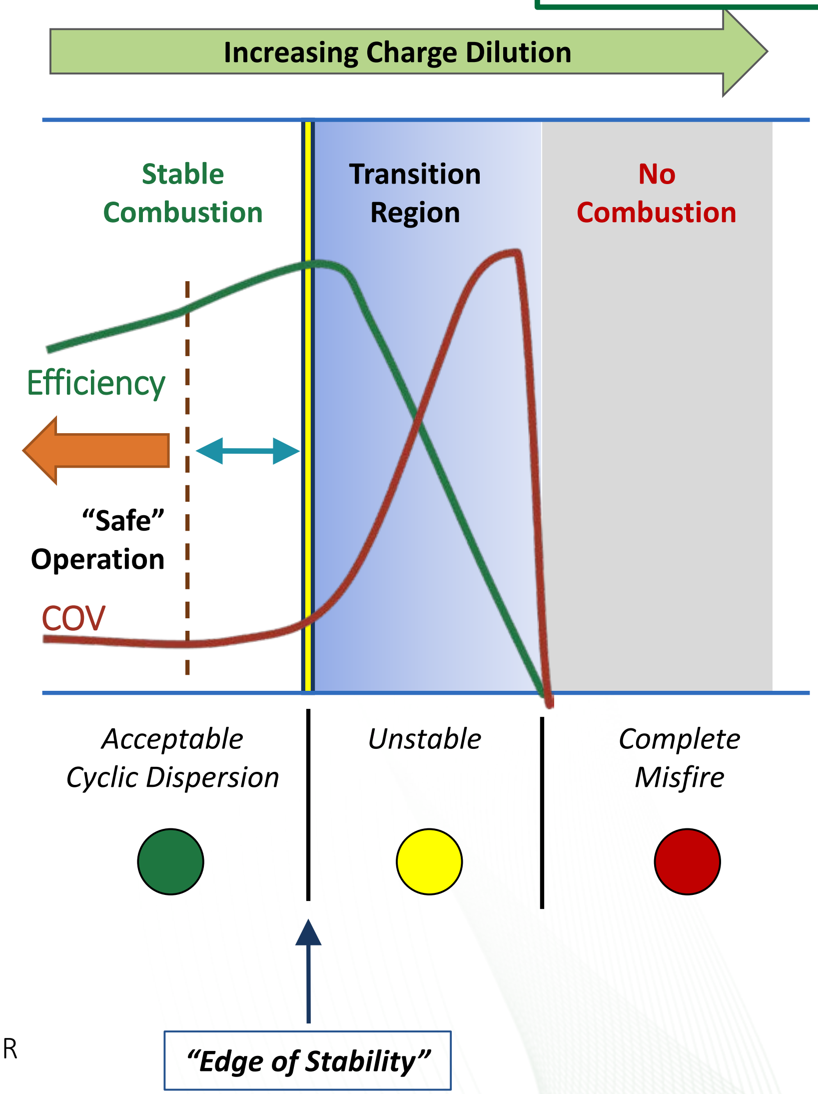
Technical Back-Up Slides

Simple representation of the onset of cycle-to-cycle instabilities

TECHNICAL BACKUP 1

- Driven by stochastic (in-cylinder variations) and deterministic (cycle-to-cycle coupling) processes
- Instabilities may be "short" or "long"[1] timescale
  - "Short" refers to a few successive cycles
  - "Long" refers to 10s-100s successive cycles
- Practical implementations operate well away from the edge of stability to avoid unintended excursions
- Advanced controls could enable operation at the "edge of stability"
  - Requires a detailed understanding of instability mechanisms



[1] Kaul BC, Finney CE, Wagner RM, Edwards ML. "Effects of External EGR Loop on Cycle-to-Cycle Dynamics of Dilute SI Combustion," SAE Int. J. Engines. 2014; 7(2), doi:10.4271/2014-01-1236.

Nonlinear dependence of combustion on composition causes chaotic behavior

TECHNICAL BACKUP 2

- Flame speed dependence on ϕ is highly nonlinear
  - System is very sensitive to small variations in composition
  - Can take advantage of this to enable active control

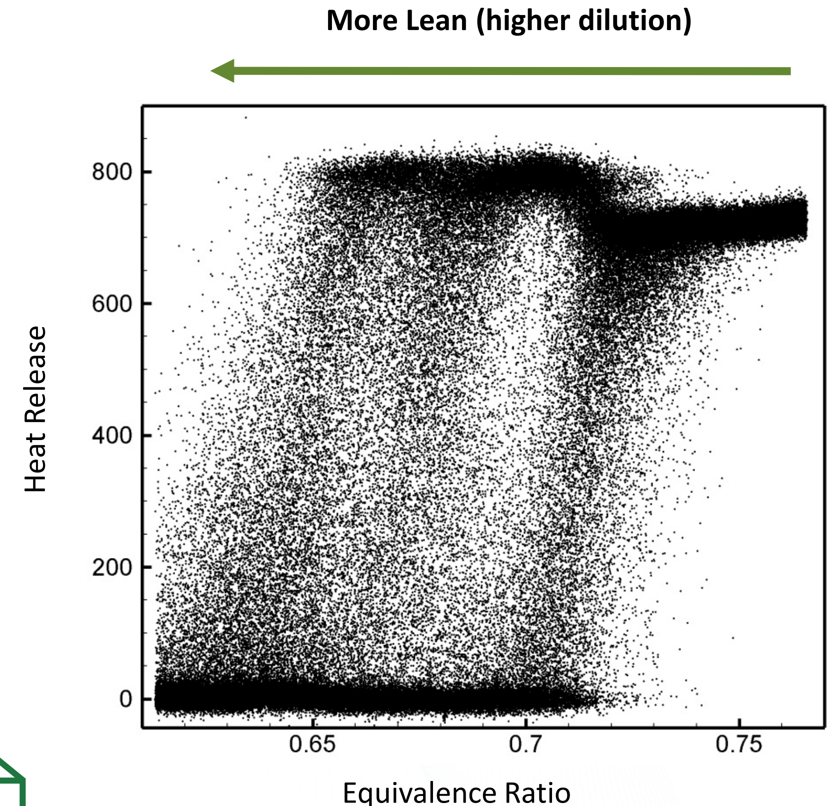
$$S_L = \boxed{S_{L0}}\left(\frac{T_u}{T_0}\right)^{\boxed{\alpha}}\left(\frac{P}{P_0}\right)^{\boxed{\beta}}\left(1-2.1Y_{dil}\right)$$

$$\boxed{S_{L0} = B_M + B_2\left(\Phi-\Phi_M\right)^2}$$

$$\alpha = 2.18-0.8\left(\Phi-1\right)$$

$$\beta = -0.16+0.22\left(\Phi-1\right)$$

Reference: B. C. Kaul, "Addressing Nonlinear Combustion Instabilities in Highly Dilute Spark Ignition Engine Operation", PhD Dissertation, Missouri University of Science and Technology, 2008.



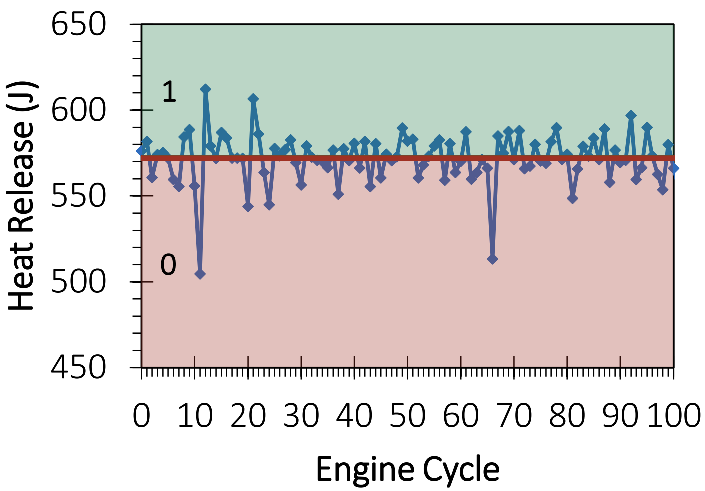
Experimental Data

Reference: R. M. Wagner, J. A. Drallmeier, and C. S. Daw, "Characterization of Lean Combustion Instability in Premixed Charge Spark Ignition Engines", International Journal of Engine Research, 1, No. 4, pp. 301-320, 2001.

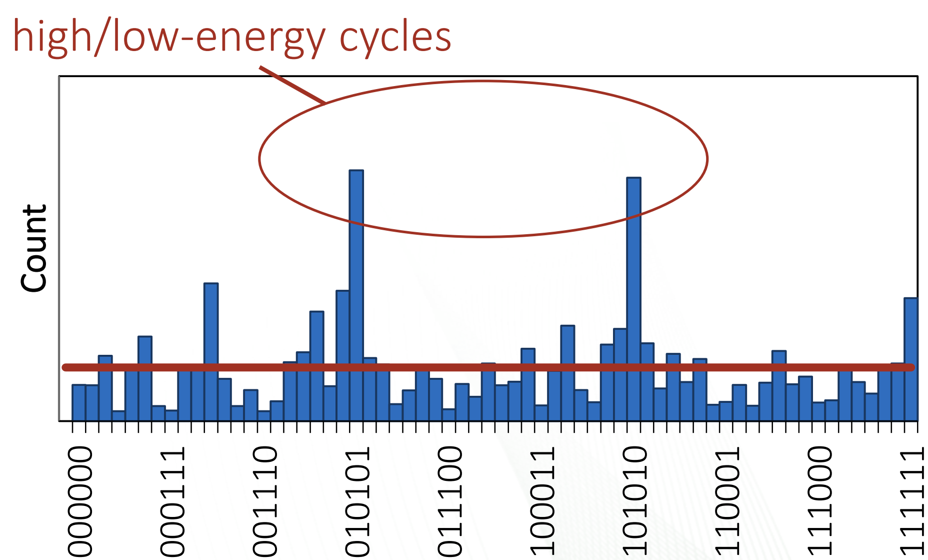
Symbol-sequence statistics analysis finds order in chaos

Technical Backup 3

- Method:
  - Partition data into discrete bins
    - Each bin is labeled with a “symbol” or “letter”
  - Identify sequences of a given number of cycles
    - These symbol sequences can be thought of as “words” made up of the symbolic “letters”
  - Detect patterns by identifying words that occur frequently
- This information will be used to enable online control of cyclic variability



Example time series with binary symbol partition

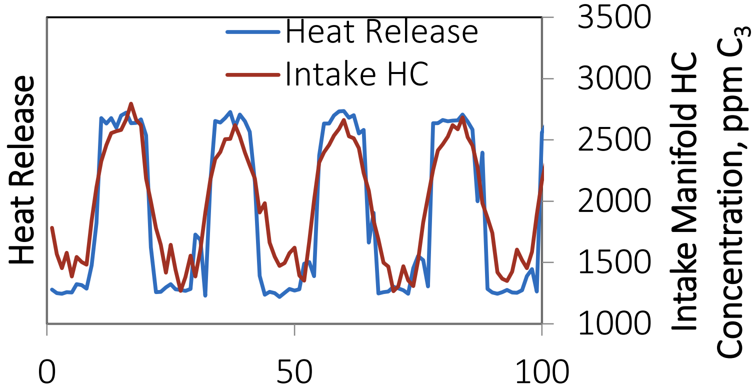


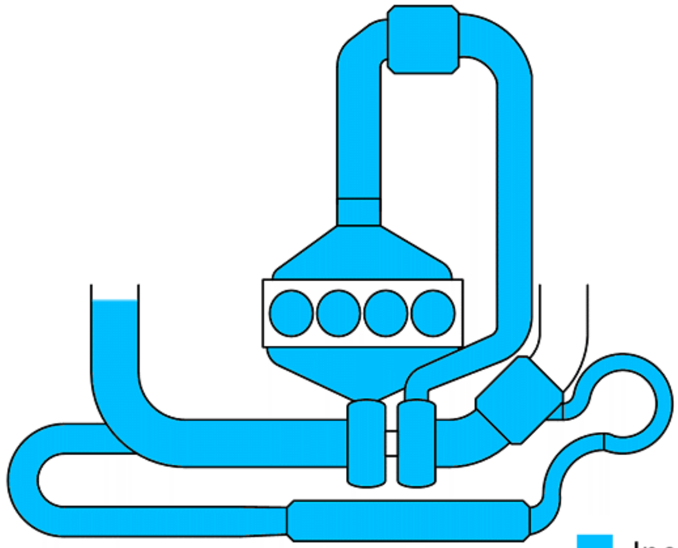
Symbol sequence histogram with 2 symbolic letters and a word length of 6

Long time-constant combustion instabilities observed for high-EGR operation

TECHNICAL BACKUP 4

- Combustion instabilities
  - Alternates between high-quality combustion and misfires
  - Period on the order of 10s of cycles
  - Variations synchronized across all 4 cylinders
- External EGR loop feedback dominates over internal residuals
  - Period of oscillations is due to flow through EGR loop
  - Recirculated exhaust from misfire cycles provides extra fuel and air
  - Recirculated exhaust from high-energy cycles provides only inert diluent

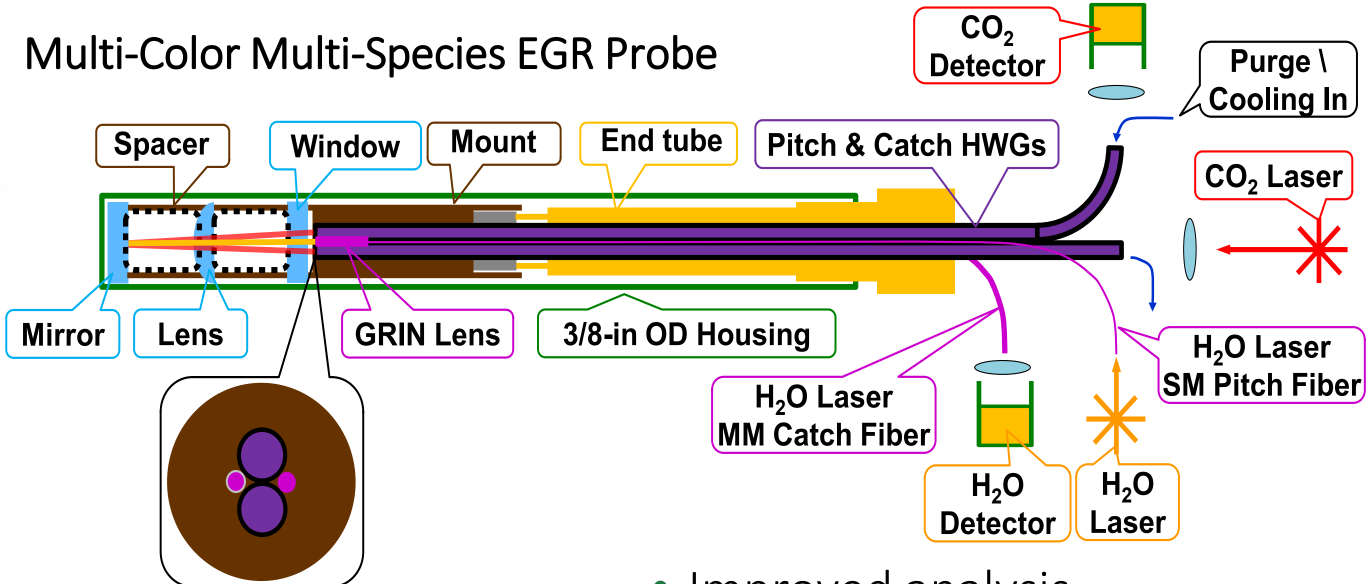




Fast EGR Measurement Probe

TECHNICAL BACKUP 5

Multi-Color Multi-Species EGR Probe



- Measures CO_2, H_2O, T & P
- Leverages ORNL–Cummins CRADA & SuperTruck
  - CRADA
    - Original EGR Probe development
  - SuperTruck
    - H_2O diagnostic development at Purdue
  - CRADA & SuperTruck
    - 4-probe multi-plex system
    - Combined CO_2–H_2O probe instrument

- Improved analysis
  - Iterative baseline fit
  - Absorption profile fit to theory (vs. integration & calibration-factors)
  - Shifted-sawtooth laser ramp for real-time background subtraction
  - Improved wavelength calibration
  - 5kHz rate (200μs, 2.4° CA at 2k RPM)